NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 13-90

A METHOD TO DETERMINE ACCURACY IN END-TIDAL CARBON DIOXIDE MONITORING

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)
An injection system was developed to determine the accuracy of end-tidal monitoring of carbon dioxide in a hyperbaric chamber. Sample tube diameter, flow rates, placement of reducing valves to control flow, and water traps were studied with sample tubes (34 m long) from 1,000 to 150 feet of sea water (FSW). A sensitive indicator of sample tube mixing is response time, defined as time to reach 90% of full scale deflection of a known calibration gas injection. From 1,000 to 380 FSW, ideal sample tube was Lee (internal diameter = 0.032 in) and from 190 to 150 FSW, Nylaflow (internal diameter = 0.078 in). Sampling rate of 2,500 ml/min, controlled at depth, gave adequate response times of 240 to 320 msec for injections from 1,000 to 150 FSW. Controlling the flow at the surface, using water traps (test tubes) and sample flows less than 2,500 ml/min prolonged the response time to unacceptable levels. This technique predetermines appropriate sample tube diameter and flow and eliminated sources of mixing to insure accurate end-tidal CO_2 measurements.

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CONTENTS

TABLE

ILLUSTRATIONS

I. INTRODUCTION

Assuming the partial pressure of carbon dioxide in alveolar air (P_ACO_2) measured from end-tidal air samples equals the partial pressure of CO_2 in arterial blood (P_ACO_2) for healthy subjects, in-line mixing of end-tidal air samples can underestimate the true value of P_ACO_2. This in-line mixing can not only yield inaccurate results, it can compromise the safety of a monitored experimental subject during strenuous underwater exercise if severe CO_2 narcosis develops (1-2). At the Navy Experimental Diving Unit (NEDU), the closest we can locate our mass spectrometer gas analyzers to the hyperbaric chamber wet pot is 34 m (110 ft). This limitation prompted us to evaluate the accuracy of end-tidal gas monitoring at various depths between 150 feet of sea water (FSW) and 1,000 FSW using an injection technique simulating the exhalation of one breath. Sample line diameter, sampling rate, placement of a reducing valve to control flow, and using a water trap to prevent moisture from entering the gas analyzer were all investigated for their effect on the accuracy of end-tidal gas analysis. This report describes the method to introduce a square wave of calibration gas and the measurements needed to help maximize accuracy for end-tidal CO_2 monitoring of an experimental subject.

II. METHODS

A. INJECTION SYSTEM

Figure 1 illustrates the injection system for introducing a square wave of calibration gas at depth inside a dry hyperbaric chamber. A 3-liter calibrated syringe (Collins, Braintree, MA), representing a typical tidal volume during moderate exercise, was flushed three times with a calibration gas (1.899% CO_2 in nitrogen). A pressure transducer (Validyne Engineering Corp., model DP-9, 0.5 psi diaphragm, Northridge, CA) was placed between the syringe and a closed 3-way valve (Collins). With pressure applied to the syringe, the sudden drop in pressure when the valve was quickly opened marked the onset of injection on a strip chart recorder. A pressure artifact at the completion of the injection allowed injection time to be measured.

The mass spectrometer sample line was placed in the center of the exhaust tube to prevent the ventilation of chamber air from diluting the sample. Flow through the sample line was controlled with a needle reducing valve (Nupro, model SS-SS2, Willoughby, OH) placed either at depth, next to the 3-way valve, as in Figure 1, or immediately before the T-block connection to the mass spectrometer at the surface. Flow was measured at the surface immediately downstream of the T-block connection with a standard air rotometer (Fischer and Porter, model 10A3555, Warminster, PA) with a range of 0 to 4,000 ml/min. The mass spectrometer was the Perkin Elmer (Marquette Gas Analysis, model MGA 1100, St. Louis, MO).

The internal diameters of the two sample lines evaluated were 0.078 in (0.198 cm) for Nylaflow tubing (Polymer Corp., Reading, PA) and 0.032 in (0.081 cm) for Lee tubing (Penn Tube, Mickleton, NJ). Both sample lines were newly constructed, standard 34 m (110 ft) long umbilicals for monitoring submerged exercising divers at NEDU. Each sample tube penetrated the hyperbaric chamber without interruption.

Small water traps have been previously used at NEDU to prevent moisture from getting into the mass spectrometer. They were small test tubes (2 and 5 ml) and a small pill bottle (20 ml). The influence of water traps placed immediately before the mass spectrometer (not shown in Figure 1) was separately evaluated.

B. MEASUREMENTS

The delay time was defined as time from the onset of injection at depth until the sample was initially recorded by the mass spectrometer. A sensitive indicator of in-line mixing is the response time, defined as the time in msec for the chart recorder to reach 90% of full scale deflection of the injected calibration gas.

C. PROTOCOL

The delay and response times for injections made directly into the mass spectrometer at the surface without the 34 m sample line were done before testing at depth. Depths for injection testing were 1,000, 844, 630, 380, 190, and 150 FSW. The influence on response time of placing the reducing valve on the surface before the T-connection, and using water traps before the mass spectrometer was studied only at 1,000 FSW.

D. DATA ANALYSIS

With time constraints of other experimental protocols during these dives, only one to three trials could be accomplished at each depth. However, high reproducibility of this technique was proven during surface testing with repeated trials. The mean $\pm$ SD are reported for each depth, but too few data points prevented statistical analysis.

III. RESULTS

In Table 1, the sample rate, response time, delay time, injection time, and number of trials are listed for injections at the surface and from 1,000 to 150 FSW. The control values for response time for injecting a sample directly into the Perkin Elmer mass spectrometer without the 34 m sample line was 109.4 $\pm$ 3.1 (SD) msec for an injection time of 167 msec. This compares favorably with the reported response time of 100 msec for the Perkin Elmer mass spectrometer. At a slower injection time of 380 msec, the response time at the surface was 128.2 $\pm$ 5.1 (SD) msec. The first injection tests under pressure were done at 1,000 FSW. In Table 1, the reducing valve was at depth. It was placed next to the injection system and water traps were not used. Using Lee tubing, flows of 1,500 ml/min or less caused prolongation of the response time compared to flows of 2,500 and 3,000 ml/min.

Figure 2 represents actual data of an injection at the surface and injections at 1,000 FSW at various flows, illustrating prolongation of both delay and response time with flows less than 2,500 ml/min. In Figure 3, all data at 1,000 FSW for response times are shown and in Figure 4, delay times, at various sampling flows. For all depths, with the sampling rate of 2,500

ml/min, the response times for Lee and Nylaflow tubing is shown in Figure 5 with control data of injections directly into the mass spectrometer.

Lee tubing provided the fastest response times between depths of 1,000 to 380 FSW. Although the rotometer was calibrated to measure air flow and not helium-oxygen flow, it served as a relative indicator of flow. Overall, sampling rates at or above 2,500 ml/min gave the fastest response times of 230 to 320 msec for testing between 1,000 and 380 FSW.

For testing at 190 and 150 FSW with air in the hyperbaric chamber, Lee tubing was too small in diameter to provide a sufficient flow of 2,500 ml/min. Nylaflow tubing with flow controlled to 2,500 ml/min gave the fastest response times of 290 to 320 msec for 190 and 150 FSW, respectively, shown in Table 1.

At 1,000 FSW, moving the needle reducing valve from the injection system at depth to immediately before the mass spectrometer at the surface increased the delay from 1,700 msec to 13.5 sec due to compression of the gas sample in the 34 m of tubing. This caused so much in-line mixing that 90% of full scale deflection was never achieved.

All water traps created a mixing chamber which greatly increased response times. For the smallest test tube (2 ml) the response time increased from 240 msec to 600 msec at 1,000 FSW sampling at 2,500 ml/min. The 5 ml test tube and 20 ml pill bottle caused so much mixing that 90% of full scale deflection was never achieved preventing calculation of response time.

IV. DISCUSSION

The injection system tested at the surface compared favorably with the response time reported by the manufacturer of the mass spectrometer. The high reproducibility reflected by a very small standard deviation during surface testing demonstrated that only a few tests were needed at depth to: (1) measure response time and delay at various flows and, (2) to determine any influence of sample tube diameter, reducing valve position, and water traps on response time.

In our hyperbaric complex, sampling from depths of 1,000 to 380 FSW should be done with Lee tubing with flow rates of 2,500 ml/min to provide the quickest response times of 240 to 320 msec. End-tidal gas sampling for depths of 190 FSW to 150 FSW requires Nylaflow tubing since inadequate sampling flow with Lee tubing caused in-line mixing. Eliminating water traps and placing the needle reducing valve at the diver's helmet will reduce the response time to acceptable levels, providing sufficient flow (2,500 ml/min) is maintained. Delay time ranged from 1.7 sec at 1,000 FSW to 3.3 sec at 150 FSW. This allows direct comparison of breath-to-breath and end-tidal CO_2 with mouth pressure recordings. Further testing is needed between 380 and 190 FSW and shallower than 150 FSW to determine the ideal sample line diameter and flow rate.

Figure 2 illustrates that if data is overlaid and compared by sampling rate, below 2,500 ml/min the response time is obviously prolonged. However, for a group of volunteers in our laboratory familiar with this injection technique, this was not apparent by simple visual inspection of various data of

waveforms of injections with unknown sampling rates. Direct calculation of the response time to 90% full scale deflection was needed to verify which tests were done at sampling rates at or above 2,500 ml/min.

V. CONCLUSION

By using this injection technique, the appropriate sample tube diameter and flow can be predetermined and sources of in-line mixing eliminated to insure accurate measurement of end-tidal CO_2. For typical respiratory rates of 25 to 30 breaths/min observed at NEDU during heavy underwater exercise with deep air and mixed gas diving (1-2), the response times measured in this study are acceptable for the accurate determination of end-tidal carbon dioxide. Simple visual inspection of the end-tidal gas waveform from an experimental subject cannot verify accuracy for breath-to-breath analysis of carbon dioxide.

REFERENCES

1. Sterba JA. Hypercapnia during deep air and mixed gas diving. Navy Experimental diving Unit (Panama City, FL) Report 12-90. May, 1990.

2. Sterba JA. Hypercapnia during deep air and mixed gas diving. Undersea Biomed Res 1990; submitted for publication.

Table #1

INJECTION STUDY: SURFACE AND 150-1000 FSW
mean ± SD

Depth (FSW)	Sample Rate (ml/min)	Response Time (msec)	Delay Time (msec)	Injection Time (msec)	# of trials (n)
1000[a]	750	563.3 ± 55.1	3166.7 ± 208.2	316.7 ± 76.4	3
	1500	330.0 ± 36.0	2233.3 ± 57.7	433.3 ± 28.9	3
	2500	240.0 ± 0.0	1700.0 ± 0.0	350.0 ± 0.0	2
	3000	230.0 ± 14.1	1625.0 ± 106.1	450.0 ± 70.7	2
844[a]	2500	320.0 ± 0.0	2275.0 ± 35.3	500.0 ± 70.7	2
630[a]	2500	295.0 ± 7.1	2000.0 ± 0.0	450.0 ± 70.7	2
380[a]	2500	273.3 ± 7.5	2000.0 ± 0.0	435.0 ± 29.5	3
380[b]	2500	315.8 ± 12.0	2000.0 ± 0.0	502.5 ± 6.0	3
190[a]	1500	420	3800	500	1
190[b]	2500	290	3400	500	1
150[a]	1000	510	4150	500	1
150[b]	2500	320	3350	500	1
SURFACE[c]	62	109.4 ± 3.1	250.0 ± 0.0	167.0 ± 18.3	17
	62	128.2 ± 5.1	250.0 ± 0.0	380.0 ± 47.8	10

[a] Lee tubing, [b] Nylaflow tubing, [c] Injected directly into mass spectrometer

INJECTION SYSTEM

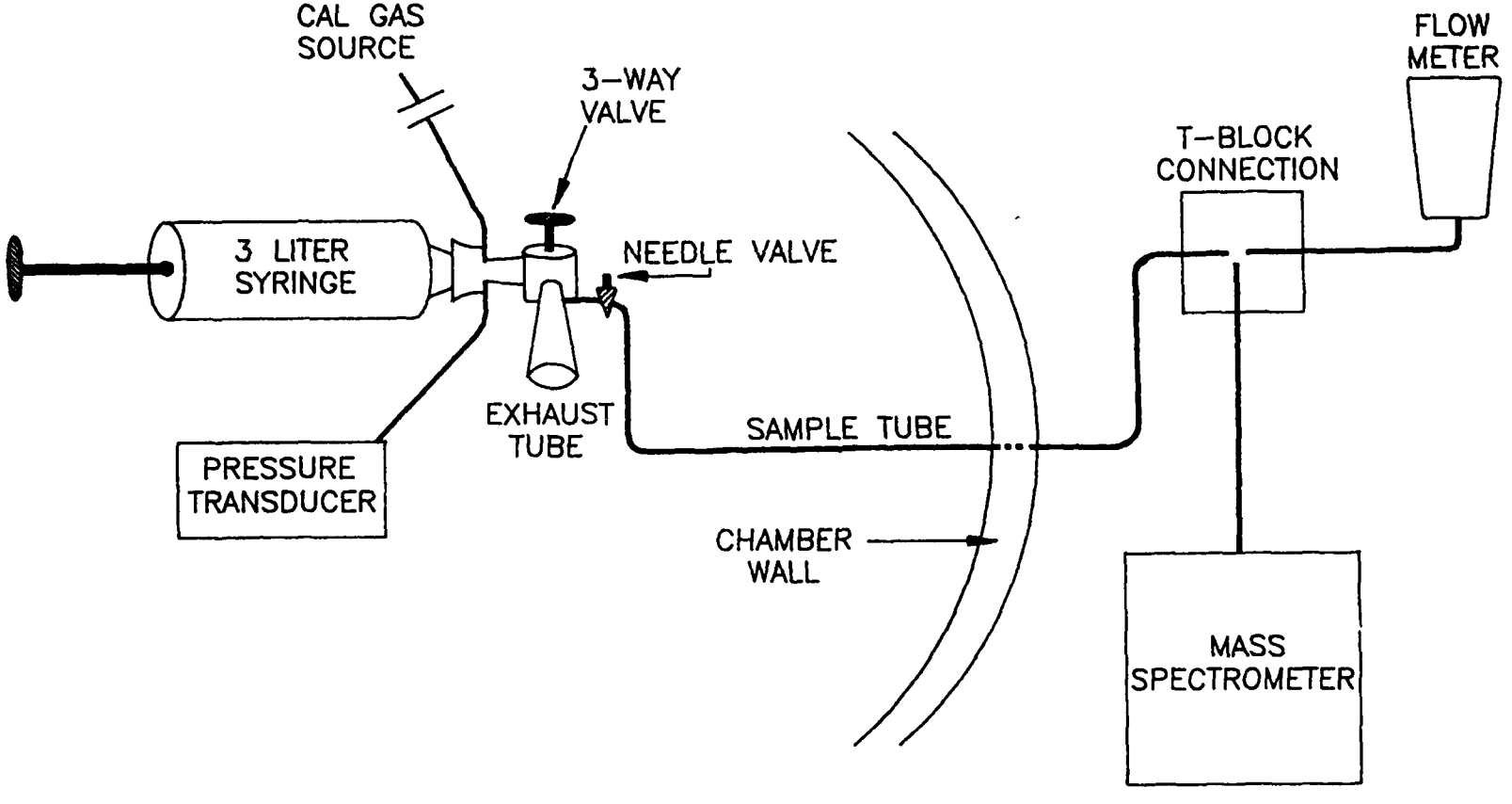

FIGURE 1

STRIP CHART RECORDINGS OF INJECTIONS AT THE SURFACE
AND
1000 FSW WITH VARYING SAMPLING RATES

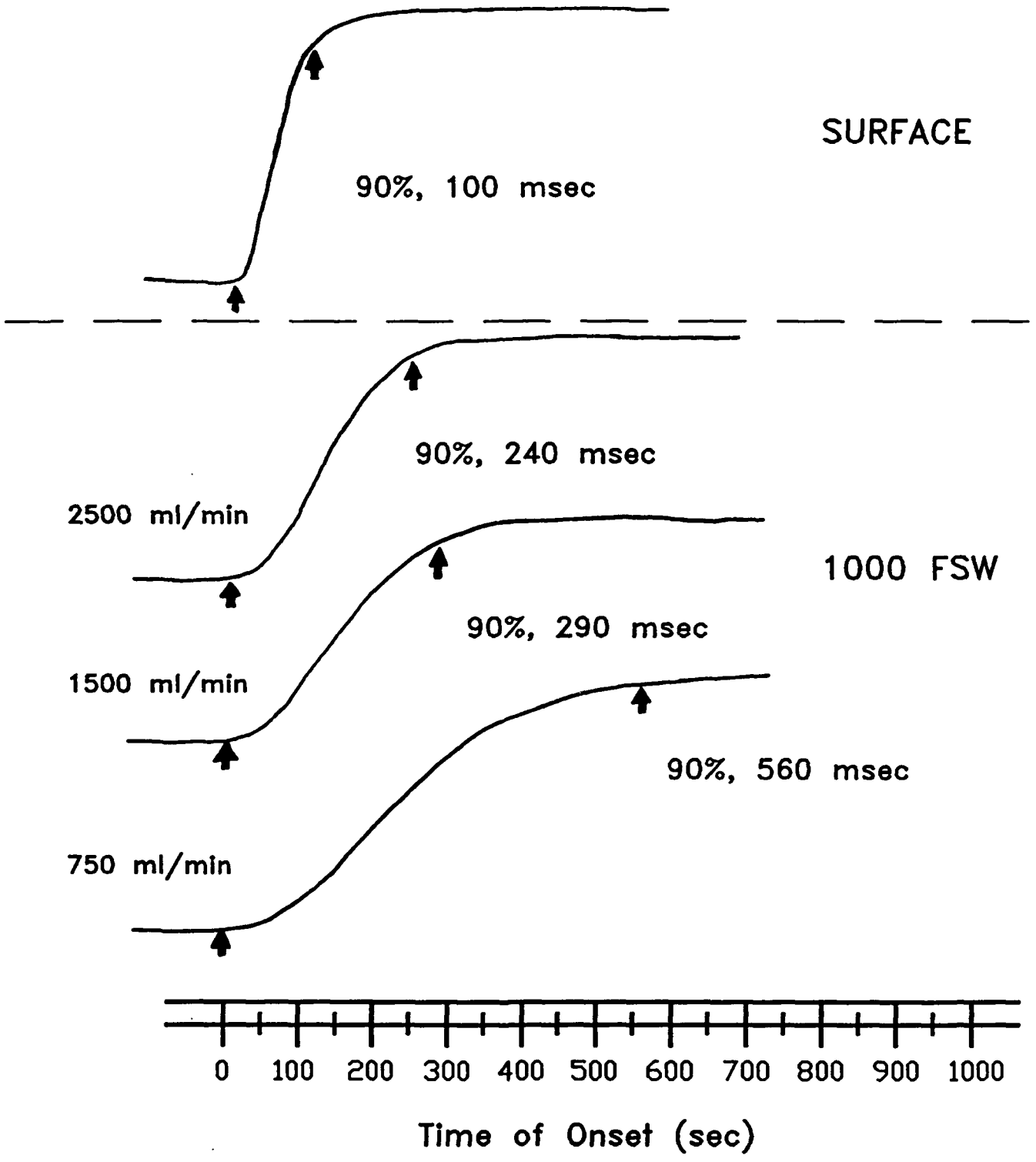

FIGURE 2.

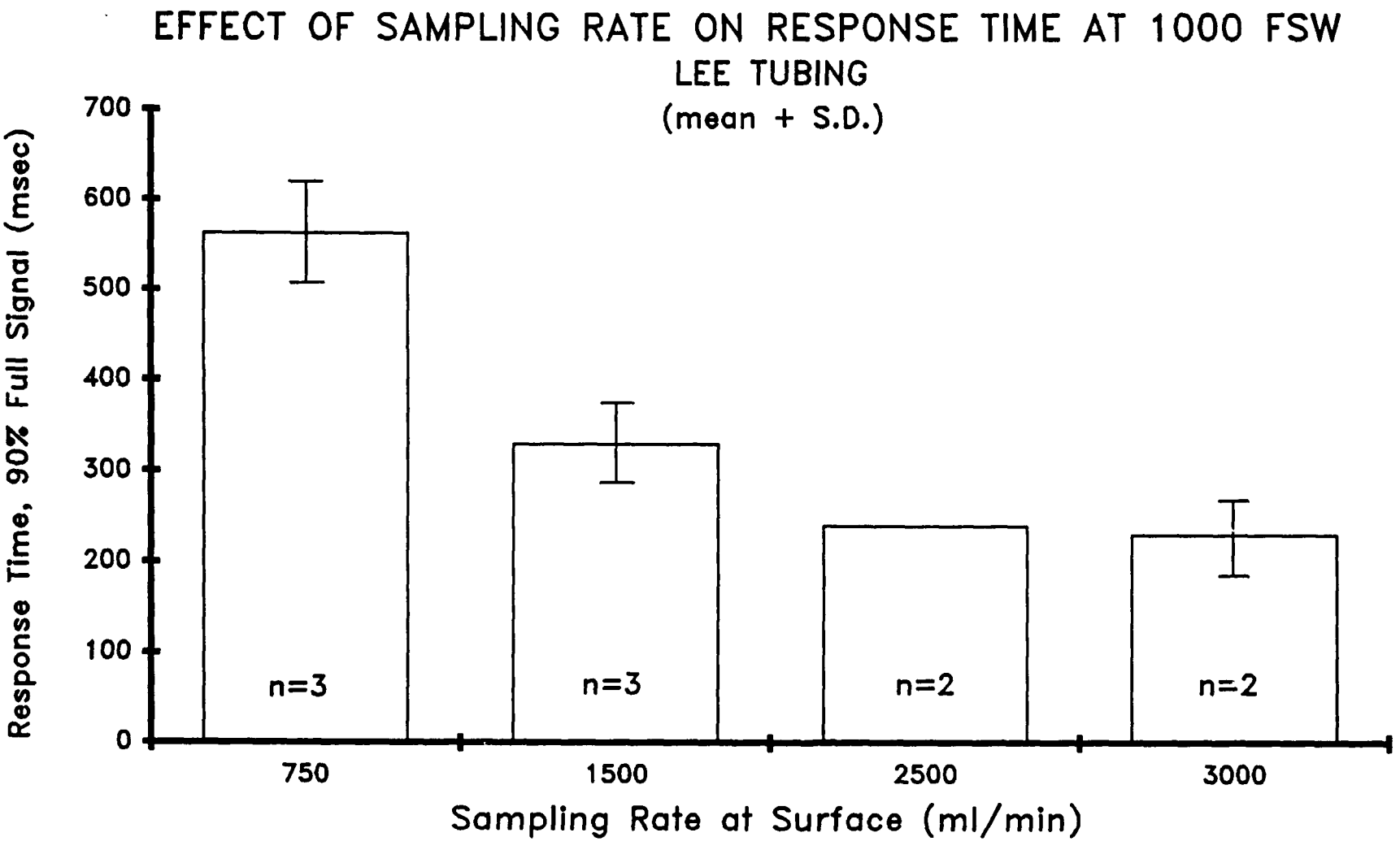
EFFECT OF SAMPLING RATE ON RESPONSE TIME AT 1000 FSW
LEE TUBING
(mean + S.D.)
Response Time, 90% Full Signal (msec)
700
600
500
400
300
200
100
0
n=3
n=3
n=2
n=2
750
1500
2500
3000
Sampling Rate at Surface (ml/min)

FIGURE 3

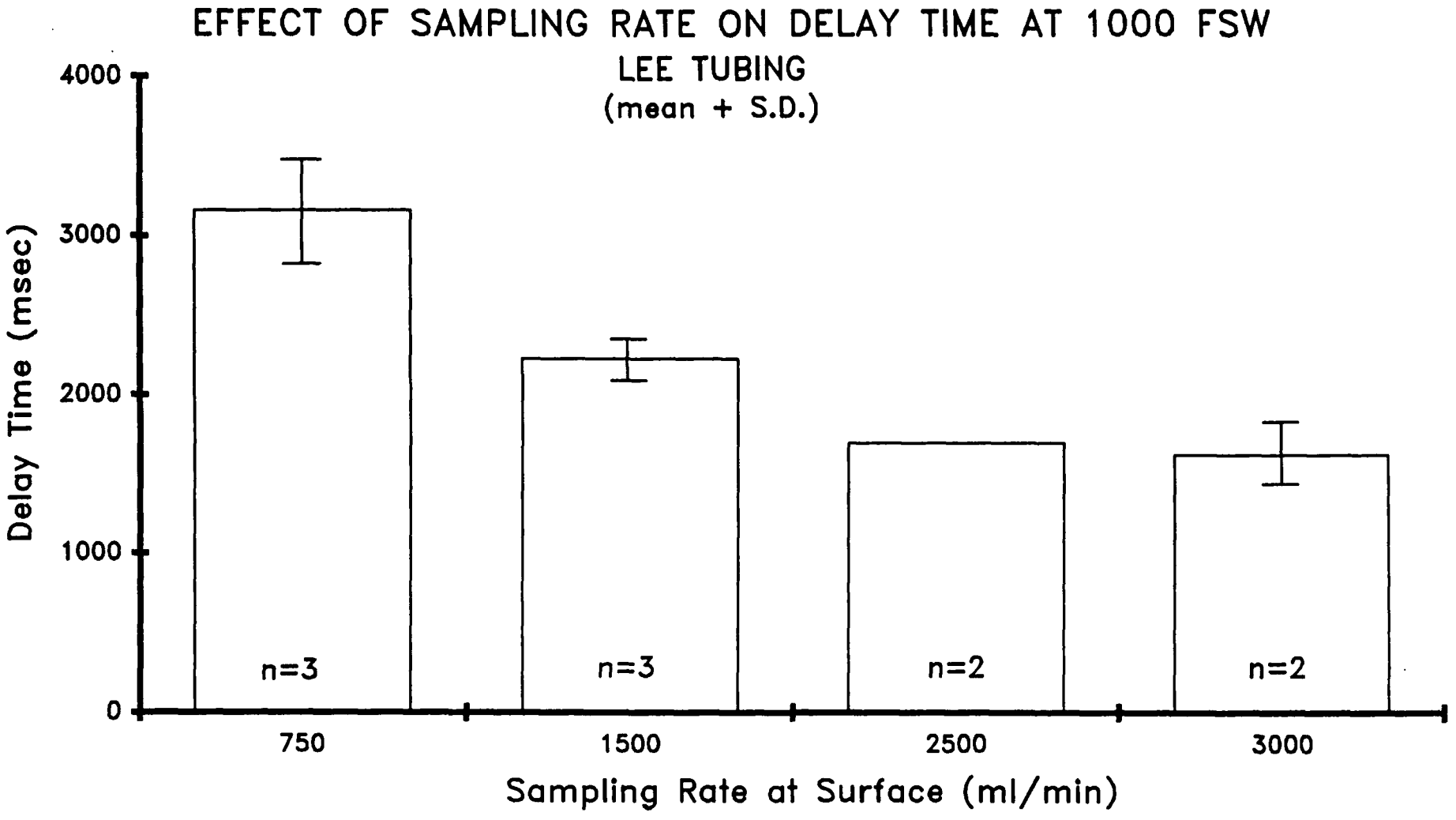
EFFECT OF SAMPLING RATE ON DELAY TIME AT 1000 FSW
LEE TUBING
(mean + S.D.)
Delay Time (msec)
4000
3000
2000
1000
0
n=3
n=3
n=2
n=2
750
1500
2500
3000
Sampling Rate at Surface (ml/min)

FIGURE 4

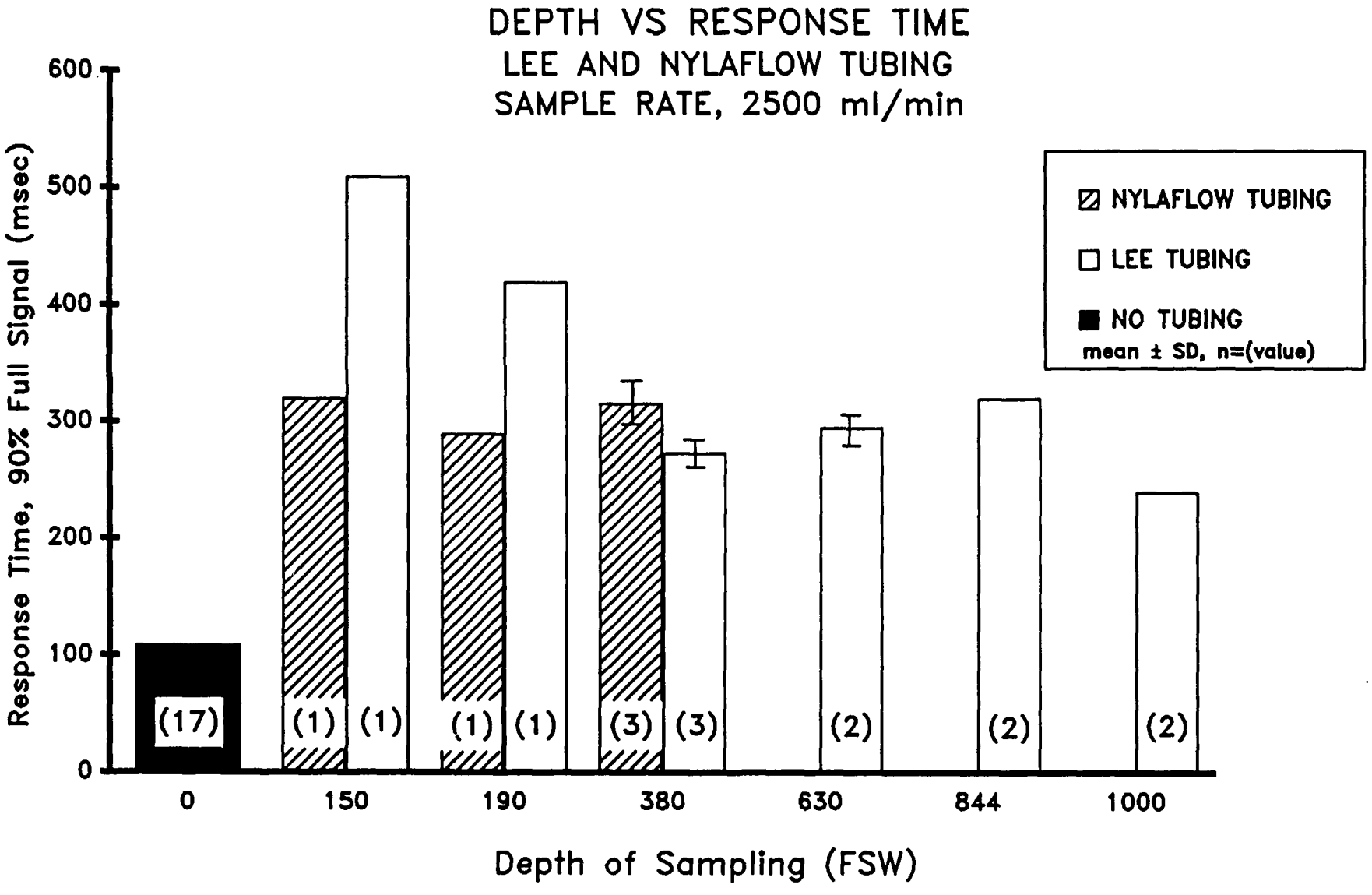
DEPTH VS RESPONSE TIME
LEE AND NYLAFLOW TUBING
SAMPLE RATE, 2500 ml/min
Response Time, 90% Full Signal (msec)
600
500
400
300
200
100
0
NYLAFLOW TUBING
LEE TUBING
NO TUBING
mean ± SD, n=(value)
(17)
(1)
(1)
(1)
(1)
(3)
(3)
(2)
(2)
(2)
0
150
190
380
630
844
1000
Depth of Sampling (FSW)

FIGURE 5